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The Impact of Macroeconomic Complexity on Environmental Pollution in Indonesia (1989-2024): An Empirical Study Using the Autoregressive Distributed Lag Approach

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Abstract
Environmental pollution caused by increasing carbon dioxide (CO_2) emissions has become an important issue in Indonesia due to rapid economic growth, industrialization, and dependence on fossil fuels. Understanding the relationship between macroeconomic dynamics and environmental degradation is essential to support sustainable development and emission reduction targets. This study aims to analyze the impact of macroeconomic complexity on environmental pollution in Indonesia during 1989-2024 using the Autoregressive Distributed Lag (ARDL) approach. The variables examined include economic growth, interest rates, inflation, foreign direct investment (FDI), energy consumption, and international trade openness on CO_2 emissions. The findings reveal a long-run cointegration relationship among the variables. Economic growth, interest rates, and energy consumption positively and significantly affect CO_2 emissions, indicating that Indonesia remains in the early stage of the Environmental Kuznets Curve (EKC). Meanwhile, international trade openness has a negative and significant effect on emissions through technological efficiency and cleaner production practices. Inflation and FDI show insignificant effects in the long run. These findings highlight the importance of integrating macroeconomic, energy, and environmental policies through renewable energy transition, green investment, and sustainable trade strategies to achieve Indonesia's emission reduction target by 2030.

INTRODUCTION

The increase in global economic activity over the past three decades has significantly accelerated economic growth but has also placed serious pressure on environmental quality. Accelerated economic development is generally accompanied by increased consumption of fossil fuels, the expansion of international trade, and industrial activities that contribute to rising carbon dioxide (CO_2) emissions. The report by the Intergovernmental Panel on Climate Change (IPCC, 2023) indicates that more than 75% of the rise in global temperatures since the pre-industrial era is attributable to increased carbon dioxide (CO_2) emissions from the industrial and energy sectors. (Calvin et al., 2023). This phenomenon suggests that accelerated economic development that is not accompanied by structural transformation and an energy transition has the potential to exacerbate climate conditions. (Chen et al., 2021; Jian et al., 2019).

Global concern over climate change was reflected in international commitments made at the climate change conference, the 21stSession of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21 UNFCCC) in Paris, France, in 2015. This meeting resulted in a convention of great significance for global climate change issues, namely the Paris Agreement. Indonesia demonstrated a serious commitment to addressing climate change by ratifying the Paris Agreement in 2015 and enacting it into Law No. 16 in 2016. This was communicated through the Nationally Determined Contribution (NDC) in 2016 and subsequently updated with the Enhanced NDC in 2021. Through the Enhanced NDC, Indonesia aims to reduce greenhouse gas (GHG) emissions by 31.89% through national efforts and by 43.2% with international support by 2030.

Rapid economic growth driven by industrialisation in developing countries tends to result in more widespread environmental damage. When a country seeks to expand industrial activity and focuses on production to achieve prosperity, the environment tends to be the last consideration in its economic growth strategy (Mahmood et al., 2020). Indonesia, as a developing country with the largest economy in Southeast Asia, faces a dilemma between efforts to reduce CO_2 emissions to meet its NDC targets and efforts to accelerate economic development by capitalising on the demographic dividend to escape the middle-income trap (Wisnubroto Kristantyo, 2024).

Indonesia's economic growth over the past three decades has shown an upward trend during the period 1989-2024, with an average annual growth rate of 4.79 per cent, despite experiencing contractions during the 1998 economic crisis and the COVID-19 pandemic in 2020. According to BPS data, Indonesia's economic growth has tended to be underpinned by various key sectors such as manufacturing, mining, infrastructure development, transport, and the expansion of natural resource-based industries such as coal and palm oil. The development of these sectors reflects the increasing industrialisation and national economic development oriented towards boosting production output, trade, and public consumption. In addition to being influenced by growth in the real sector, the dynamics of the Indonesian economy are also shaped by the complexity of macroeconomic variables such as monetary policy through interest rates, instability caused by inflation, foreign direct investment (FDI) flows, energy consumption, and the openness of international trade, all of which interact to influence economic stability and national production activity.

Increased economic activity and industrialisation have led to a continuous rise in energy consumption in Indonesia, which remains dominated by fossil fuels such as coal, crude oil and natural gas as the primary energy sources for the industrial, transport and power generation sectors. According to data from the World Bank, per capita fossil fuel consumption has risen by 4.04 per cent annually. Fossil fuels remain the primary energy source for Indonesia, accounting for an average of 95.52 per cent of total energy consumption, whilst the remainder comes from renewable energy. High levels of industrial activity, transport, international trade, and investment in the manufacturing, energy, and mining sectors have driven an increase in fossil fuel consumption and carbon emissions. In addition to the burning of fossil fuels, rising environmental pollution is also influenced by land clearing, deforestation, the expansion of industrial zones, mining, and the increase in the number of motor vehicles during the process of economic development.

Indonesia's economic growth, accompanied by a rise in per capita fossil fuel consumption, has contributed to an increase in CO2 emissions in the country. According to data from Our World in Data, CO2 emissions in Indonesia between 1989 and 2024 have shown a rapid upward trend. The average annual increase in CO2 emissions over this period was 0.061 tonnes of CO2, or 3.98 per cent. This indicates that economic growth, energy consumption, and the dynamics of macroeconomic variables such as interest rates, inflation, FDI, and international trade have both direct and indirect links to the long-term increase or decrease in environmental pollution and air quality in Indonesia.

The relationship between economic growth and environmental pollution is explained by the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between environmental pollution and economic growth or income levels; Grossman & Krueger (1991) were the first researchers to pioneer this inverted U-shaped relationship, whilst the term "Environmental Kuznets Curve" was coined by Panayotou (1993), who stated that in the early stages of development or the pre-industrial period, increasing energy demand to drive economic growth would further worsen environmental quality until a certain point (turning point) is reached. At higher levels of economic development, structural shifts occur towards information-based industries and services, more efficient technologies, and increased demands for environmental quality, which will lead to a reduction in environmental pollution (Panayotou, 1993).

Within this framework, energy consumption is a dominant factor that amplifies the impact of economic growth on environmental pollution, particularly that caused by fossil fuels through increased production scale (scale effect), especially in developing countries. Furthermore, trade openness is determined by the extent of the scale effect, composition effect, and technology effect in a given country. Meanwhile, foreign direct investment (FDI) also influences environmental pollution through production expansion, changes in industrial structure, and technology transfer, as explained in the Pollution Haven Hypothesis (Copeland & Taylor, 1994).

Beyond these factors, this study considers monetary policy as a new and relatively unexplored factor in the study of environmental pollution. Annicchiarico and Di Dio (2017) developed a New Keynesian flow-based pollutant emissions model; in this context, they demonstrated within the model that monetary policy is not neutral with regard to environmental pollution emissions. The optimal monetary policy response to environmental pollution is highly counter-cyclical. Inflation is always a monetary dilemma in the long run; therefore, inflationary instability also hinders environmental pollution. Monetary policy shocks cause an increase in interest rates, which in turn suppresses aggregate demand and thus improves environmental quality. Furthermore, inflation can be explained through Keynes' Demand-Pull Inflation Theory, which states that an increase in aggregate demand drives economic activity and energy consumption, potentially increasing emissions, whilst high inflationary pressures can reduce purchasing power and economic activity, thereby affecting levels of environmental pollution.

Some previous findings regarding the key macroeconomic determinants of environmental pollution reported in earlier studies include: Aggregate domestic demand (M. Ahmad & Khattak, 2020) indicates that innovation does not consistently reduce CO_2 emissions, although the consumption of renewable energy is capable of reducing emissions and supports the Environmental Kuznets Curve (EKC) hypothesis. Economic growth (Özokcu & Özdemir, 2017; Li et al., 2023; Khan, 2019; Maroufi & Hajilary, 2022) the research findings reveal mixed results, showing that economic growth in the early stages of development tends to increase CO_2emissions, but in the long term may reduce emissions as energy efficiency improves and technology advances; furthermore, at a certain income level, this supports the EKC hypothesis. Energy consumption and the use of fossil fuels (Jian et al., 2019; Hwang & Yoo, 2015; Mirzaei & Bekri, 2017; Xuan, 2024). Most studies have found that increased energy consumption and reliance on fossil fuels significantly increase CO_2 emissions. Globalisation (Shahbaz, Adebola, & Ozturk, 2016): research findings indicate that globalisation can either reduce or increase CO_2 emissions, depending on the economic characteristics and energy intensity of each country. International trade (Lv & Xu, 2019;

Chen et al., 2021; Derindag et al., 2023) indicates that trade openness can improve environmental quality in the short term, but has the potential to increase carbon emissions in the long term, although in certain sectors, a reduction in emissions has also been observed through improved technological efficiency. Foreign direct investment (Apergis et al., 2023; Demena & Afesorgbor, 2020) research findings indicate that FDI can increase carbon emissions through the 'pollution haven' phenomenon, yet under certain conditions it can also reduce emissions through the transfer of cleaner technologies. Urbanisation (Wang, Li, & Fang, 2018) indicates that urbanisation has a significant positive relationship with increased CO_2 emissions in the long term, although the impact may vary between countries. Fiscal policy instruments (Yuelan et al, 2019) found that expansionary fiscal policy can increase environmental degradation through increased economic activity and energy consumption. Financial sector development (Dar & Asif, 2017) found that financial sector development and increased energy consumption contribute to rising greenhouse gas emissions, although the relationship between economic growth and environmental degradation is not always statistically proven.

Given that previous findings on the macroeconomic determinants of CO_2emissions have yielded mixed empirical results, further research is needed to examine the macroeconomic impact on environmental pollution. Most studies have examined variables such as economic growth, energy consumption, international trade, and foreign direct investment, whilst the role of monetary factors such as interest rates and inflation has been relatively rarely analysed within the framework of environmental pollution. Given that many Asian countries utilise monetary policy as a key instrument to drive innovation and achieve economic stability, the author believes it is important to examine its role in mitigating environmental pollution or the potential for increased environmental pollution.

Based on this research gap, this study aims to analyse the impact of macroeconomic complexity on environmental pollution in Indonesia during the period 1989-2024 using the Autoregressive Distributed Lag (ARDL) approach developed by (Pesaran et al., 2001). This study is expected to make an empirical contribution to the economic and environmental literature by presenting a comprehensive model for understanding the relationship between macroeconomic stability and the sustainability of natural resources. Furthermore, the findings of this study are expected to inform policy-making in achieving green economic growth, supporting the clean energy transition, and strengthening Indonesia's commitment to reducing emissions by 31.89% by 2030 in line with the *Enhanced Nationally Determined Contribution* (NDC) (Wisnubroto Kristantyo, 2024).

HYPOTHESIS

Hypothesis 1:
Economic growth is thought to have a positive impact on environmental pollution in Indonesia.
Hypothesis 2:
Interest rates are thought to hurt environmental pollution in Indonesia
Hypothesis 3:
Inflation is thought to hurt environmental pollution in Indonesia
Hypothesis 4:
Foreign direct investment is thought to have a positive impact on environmental pollution in Indonesia
Hypothesis 5:
Energy consumption is thought to have a positive impact on environmental pollution in Indonesia.
Hypothesis 6:
International trade is thought to have a positive impact on environmental pollution in Indonesia

METHODS

This study employs a quantitative and descriptive approach using time series data; this is a scientific approach that prioritises the collection and analysis of data in the form of figures or variables that can be measured numerically. According to Johnson and Christensen (2017), this method aims to investigate the relationships between variables and to test hypotheses using statistical techniques. The quantitative approach was chosen because this study aims to analyse the empirical relationship between macroeconomic complexity and environmental pollution in Indonesia based on numerical data processed statistically.

The data collection method used is the documentation method, which involves collecting data by examining or analysing documents produced by the subjects themselves or by others. The documentation technique itself can be defined as a method of data collection through written materials published by the institutions that are the subject of the research. These may take the form of procedures, regulations, or reports on work results published by the institutions under study. Through this method, the researcher collects secondary data that has been published by various official agencies or institutions. This data is then collected, recorded, and reprocessed in accordance with the research requirements. The documentation method was chosen because it is considered efficient in obtaining data that is systematically available, valid, and reliable, thereby supporting the empirical analysis required in the research.

The data used consists of annual time series data covering a 35-year observation period from 1989 to 2024, aligned with the availability of secondary data from Our World in Data (OWD), the World Bank (World Development Indicators (WDI)), Federal Reserve Bank of St. Louis (FRED).

Some data missing at the beginning and end of the period were estimated using the Quadratic Match Average interpolation method to ensure consistency in annual frequency. Operational definitions of variables were used to describe the indicators employed in measuring each research variable, enabling empirical analysis.

Table 1.1 Operational Definitions of Variables

Variable	Kode	Description	Unit	Source
CO2 emissions per capita	CO2	Carbon dioxide emissions resulting from the combustion of carbon-containing materials or compounds, such as fossil fuels and industrial processes, divided by the population.	Million tonnes	Our World in Data
Policy Interest Rate	IR	Central Bank Interest Rates: Total for Indonesia	Percentage (%)	Federal Reserve Bank of St. Louis
Gross Domestic Product (GDP Growth Rate)	GDP	Gross Domestic Product (GDP) growth (year-on-year %)	Annual percentage (%	World Bank Database
Inflation (Consumer Price Index)	INF	Consumer price inflation (year-on-year %)	Annual percentage (%	World Bank Database
Foreign Direct Investment (FDI Inflow)	FDI	Foreign direct investment, net inflows (% of GDP)	Percentage of GDP	World Bank Database
Fossil Energy Consumption per Capita	EC	The total consumption of fossil fuels, such as crude oil, natural gas, and coal, divided by the population.	Terawatt-hours (TWh)	World Bank Database

Trade Openness	TO	The total value of exports and imports of goods and services divided by GDP.	Percentage of GDP	World Bank Database

The analytical tool used in this study is the Autoregressive Distributed Lag (ARDL) model developed by Pesaran et al. (2001). The ARDL model was chosen because it is capable of analysing both short-term and long-term relationships between variables despite differing levels of integration, namely I(0) or I(1). The data analysis process began with a stationarity test, the determination of the optimal lag based on information criteria (AIC, SC, and HQC), and a cointegration test using the Bounds Test. Once cointegration was confirmed, ARDL estimation was carried out. Subsequently, the short-run model was estimated in the form of an Error Correction Term (ECT) to capture short-run dynamics and adjustments towards long-run equilibrium, and the long-run model was estimated using the following equation:

$$\Delta EmisiCO2_t = a_0 + \sum_{i=1}^{p} a_1 \Delta EmisiC02_{t-1} + \sum_{i=1}^{q} a_2 \Delta Int_{t-1} + \sum_{i=1}^{q} a_3 \Delta Gdp_{t-1} + \sum_{i=1}^{q} a_4 \Delta Inf_{t-1} + \sum_{i=1}^{q} a_5 \Delta Fdi_{t-1} + \sum_{i=1}^{q} a_6 \Delta Ec_{t-1} + \sum_{i=1}^{q} a_{7i} \Delta Trade_{t-1} + \beta_1 Int_{t-1} + \beta_2 Gdp_{t-1} + \beta_3 Inf_{t-1} + \beta_4 Fdi_{t-1} + \beta_5 Ec_{t-1} + \beta_6 Trade_{t-1} + \varepsilon_t.$$

Diagnostic tests were then carried out, including tests for normality, multicollinearity, autocorrelation, heteroscedasticity, the Ramsey RESET test, and the CUSUM and CUSUMSQ stability tests. All data processing was carried out using EViews 12.

RESULTS AND DISCUSSION

1. Variable Description

Table 1.2 Results of the Descriptive Analysis

Variabels	Mean	Maximum	Minimum	Std. Dev	Obs
Emisico2	12.536419	28650963	0.730701	7331688.	35
Ir	10.59778	38.44000	3.500000	6.749977	35
Gdp	4.799632	8.220007	-13.12673	3.588640	35
Inf	8.262990	58.45104	1.560130	9.385564	35
Fdi	1.291690	2.916115	-2.757440	1.286008	35
Ec	81.37426	100.2539	62.64010	12.29952	35
To	52.12146	96.18619	32.97218	11.68239	35

Source: Secondary data analysed using Eviews 12

Table 1.1, the results of the descriptive statistical analysis, show that all variables exhibit data variation over the observation period 1989-2024, with a total of 35 observations. The CO_2 emissions variable has a mean value of 12,536,419; the interest rate (IR) is 10.59%, economic growth (GDP) is 4.79%, inflation (INF) is 8.26%, FDI is 1.29%, energy consumption (EC) is 81.37, and trade openness (TO) is 52.12%.

2. Stationarity Test

Table 1.3 Results of the Unit-Level Root Test

Variable	*Level*	*Ordo of*

	t-statistics	*Prob.*	*McKinnon's Critical Value (5%)*	*Integration*
EmisiCO_2(Y)	-1.329495	0.6044	-2,96	Non-stationary
IR (X1)	-0.703784	0.8304	-2,96	Non-stationary
GDP (X2)	-4.311754	0.0017	-2,96	Stationary
INF (X3)	-4.002347	0.0050	-2,96	Stationary
FDI (X4)	-2.334733	0.1673	-2,96	Non-stationary
EC (X5)	-0.755269	0.8192	-2,96	Non-stationary
TO (X6)	-0.993418	0.7441	-2,96	Non-stationary

Source: Secondary data analysed using Eviews 12

According to Table 1.2, the results of the ADF unit root test at the level, yielding stationary data, are the GDP (X2) and INF (X3) variables. Meanwhile, the CO2 emissions, IR, FDI, EC, and TO variables are not yet stationary.

Table 1.4 Results of the Unit Root Test for First Differences

Variabel	*First Difference*			*Ordo of Integration*
	t-statistics	*Prob.*	*McKinnon's Critical Value (5%)*	
EmisiCO_2(Y)	-8.226111	0.0000	-2,96	Stationary
IR (X1)	-3.755358	0.0083	-2,96	Stationary
GDP (X2)	-6.097230	0.0000	-2,96	Stationary
INF (X3)	-7.187243	0.0000	-2,96	Stationary
FDI (X4)	-5.633840	0.0000	-2,96	Stationary
EC (X5)	-5.635657	0.0000	-2,96	Stationary
TO (X6)	-6.226916	0.0000	-2,96	Stationary

Source: Secondary data analysed using Eviews 12

Following the ADF Unit Root Test on the first differences of the variables CO_2 emissions, IR, FDI, EC, and TO, these were found to be stationary, as the respective t-statistics were all smaller than McKinnon's 5% critical value (-2.96). Consequently, all variables can be used for ARDL analysis as they exhibit a combination of I(0) and I(1) integration orders.

3. Optimum Lag Test

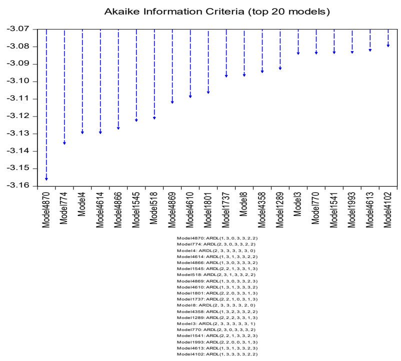


Figure 1.1

Optimum Lag Results from the Akaike Information Criterion

Source: Secondary data analysed using Eviews 12

The optimal lag is indicated by the highest number of asterisks; the results of the lag length criteria in the graph indicate that the dependent variable used is lag 1, and the maximum independent variable lag is lag 3. The following are the results of the AIC test to determine the maximum lag for the ARDL model, namely (1,3,0,3,3,2,2) for each of the seven variables.

4. Bounds Test

Table 1.5 F-Bounds Test

	Value	Signif	I(0)	I(1)
F-statistic	**7.433332**	10%	1.99	2.94
K	6	**5%**	**2.27**	**3.28**
		2.5%	2.55	3.61
		1%	2.88	3.99

Source: Secondary data analysed using Eviews 12

The results of the F-bound test show that the F-statistic value of 7.433332 is greater than the upper bound for I(1) at all significance levels, namely 10% (2.94), 5% (3.28), 2.5% (3.61) and 1% (3.99). Consequently, it can be concluded that H0, which states the absence of cointegration, is rejected, and H1 is accepted, meaning there is a long-run (*long-run cointegration* between the dependent variable (CO_2 emissions) and the independent variables representing macroeconomic complexity (interest rates, economic growth, inflation, foreign direct investment, energy consumption, and international trade).

5. **ARDL Estimation Results**

Table 1. 6 ARDL Estimation

Method: ARDL					
Selected model: ARDL (1,3,0,3,3,2,2)					
Variable	Coefficient	Std. Error	t-Statistic	Prob.	Description
D(LNCO2(-1))	-0.041664	0.040915	-1.018304	0.3304	Not significant
D(IR)	-1.069147	0.176253	-6.065996	0.0001	Significant
D(IR(-1))	0.028932	0.011426	2.532267	0.0279	Significant
D(IR(-2))	0.018119	0.006719	2.696530	0.0208	Significant
D(IR(-3))	0.001838	0.002339	0.785994	0.4485	Not significant
GDP	-0.008159	0.026861	-0.303728	0.7670	Not significant
INF	1.456311	0.687336	2.118775	0.0577	Significant
INF(-1)	-0.473059	0.334729	-1.413258	0.1852	Not significant
INF(-2)	0.004215	0.004556	0.925225	0.3747	Not significant
INF(-3)	-0.028034	0.007952	-3.525485	0.0048	Significant
D(FDI)	-0.006382	0.003463	-1.843134	0.0924	Not significant
D(FDI(-1))	0.003807	0.003011	1.264266	0.2323	Not significant
D(FDI(-2))	0.000856	0.003481	0.245956	0.8102	Not significant
D(FDI(-3))	-0.006856	0.002925	-2.344451	0.0389	Significant
D(LNEC)	0.004872	0.016610	0.293299	0.7748	Not significant
D(LNEC(-1))	0.004864	0.018929	0.256960	0.8020	Not significant
D(LNEC(-2))	0.017468	0.012007	1.454830	0.1737	Not significant
D(LNTO)	0.101413	0.369582	0.274399	0.7889	Not significant
D(LNTO(-1))	-0.671017	0.317250	-2.115101	0.0581	Significant
D(LNTO(-2))	-0.191515	0.159011	-1.204417	0.2537	Not significant
C	0.391391	0.156375	2.502897	0.0294	Significant

R-squared	0.869878	Mean dependent var	0.031408
Adjusted R-squared	0.633294	S.D. dependent var	0.072974
S.E. of regression	0.044190	Akaike info criterion	-3.155972
Sum squared resid	0.021480	Schwarz criterion	-2.194083
Log likelihood	71.49556	Hannan-Quinn criter.	-2.837133
F-statistic	3.676815	Durbin-Watson stat	2.188579
Prob(F-statistic)	0.015309		

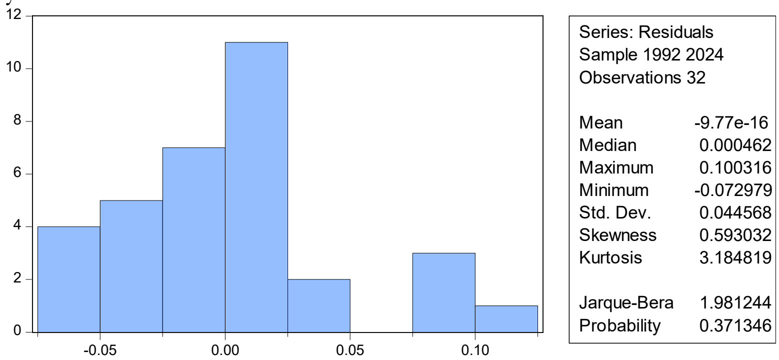
Source: Secondary data analysed using Eviews 12

Based on Table 1.7, the significant variables are D(IR), D(INT(-1)), D(INT(-2)), INF,

INF(-3), D(FDI), D(FDI(-3)), and D(LNTO(-1)), which have calculated t-values of (-6.066, 2.532, 2.697, 2.118775, -3.525485, -2.344451, and -2.115101) which are greater than the critical t-value (1.699) at the 5% level. Meanwhile, the *R-squared* value is 0.869878, indicating that 86.99% of the variation in the dependent variable can be explained by the independent variables in the model. The DW value is 2.188579, which is generally interpreted as an indication that there are no serious issues with autocorrelation in the residuals (model error). The F-statistic value is 3.676815, with a critical F-value of 2.432 at α = 5%. It can be concluded that the calculated F-value is greater than the critical F-value, indicating that the independent variables in the model significantly influence the dependent variable collectively.

6. Diagnostic Test

a. Normality Test



Game 1.2
Results of the Normality Test

Source: Secondary data analysed using Eviews 12

The results of the normality test showed a Jarque-Bera value of 1.981244 and a probability of 0.371346, indicating that the residuals are normally distributed with a probability greater than 0.05.

b. Autocorrelation Test

Table 1.7 Results of the Autocorrelation Test

Breusch-Godfrey Serial Correlation LM Test:
Null hypothesis: No serial correlation at up to 2 lags

F-statistic	0.973967	Prob. F(2,9)	0.4141
Obs*R-squared	5.693669	Prob. Chi-Square(2)	0.0580

Source: Secondary data analysed using Eviews 12

The results show that Prob. F = 0.4141 and Prob. Chi-Square = 0.0580, both of which are greater than 0.05. This indicates that there is no autocorrelation in the model, meaning that the residuals are independent across observations.

c. Ramsey Test RESET

Table 1.8 Results of the Ramsey RESET Test

	Value	df	Probability
t-statistic	0.046863	10	0.9635
F-statistic	0.002196	(1, 10)	0.9635

Likelihood ratio	0.007027	1	0.9332

Source: Secondary data analysed using Eviews 12

The probability values for the t-statistic = 0.9635, the F-statistic = 0.9635, and the likelihood ratio = 0.9332 are all > 0.05. This indicates that the model does not suffer from specification issues.

d. Heteroscedasticity Test

Table 1.9 Results of the Autocorrelation Test

Heteroskedasticity Test: Breusch-Pagan-Godfrey
Null hypothesis: Homoskedasticity

F-statistic	0.690161	Prob. F(20,11)	0.7732
Obs*R-squared	17.80829	Prob. Chi-Square(20)	0.6000
Scaled explained SS	4.030878	Prob. Chi-Square(20)	1.0000

Source: Secondary data analysed using Eviews 12

The results show that Prob. F = 0.7732 and Prob. Obs*R-squared = 0.6000, both of which are greater than 0.05. This indicates that there is no issue of heteroscedasticity, meaning that the model residuals are homogeneous across all observations.

7. Short-Run ARDL Estimation

Table 1.10 Short-Run ARDL Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.	Description
D(IR,2)	0.004215	0.002675	1.575715	0.1434	Not significant
D(IR(-1),2)	-0.028034	0.003982	-7.040651	0.0000	Significant
D(IR(-2),2)	-0.006382	0.001862	-3.428242	0.0056	Significant
D(INF)	0.003807	0.001752	2.173530	0.0525	Significant
D(INF(-1))	0.000856	0.002356	0.363435	0.7232	Not significant
D(INF(-2))	-0.006856	0.001682	-4.076013	0.0018	Significant
D(FDI,2)	0.004872	0.010328	0.471667	0.6464	Not significant
D(FDI(-1),2)	0.004864	0.011210	0.433897	0.6728	Not significant
D(FDI(-2),2)	0.017468	0.008161	2.140412	0.0556	Significant
D(LNEC,2)	0.101413	0.185099	0.547887	0.5947	Not significant
D(LNEC(-1),2)	-0.671017	0.213099	-3.148842	0.0093	Significant
D(LNTO,2)	-0.191515	0.072034	-2.658668	0.0222	Significant
D(LNTO(-1),2)	0.391391	0.065668	5.960116	0.0001	Significant
CointEq(-1)*	-1.069147	0.108383	-9.864536	0.0000	Significant

Source: Secondary data analysed using Eviews 12

Based on Table 1.12, the short-run ARDL estimates show a CointEq(-1) value of -1.069147 and a coefficient of 106.91%, indicating that the imbalance will be fully corrected within less than one year. Significance (t-statistic = -9.864536, Prob. = 0.0000) indicates that the CointEq(-1) coefficient is significant, meaning that this variable plays a key role in restoring long-term equilibrium following a disturbance. The interest rate variable (D(IR)) is significant at lags 1 and 2, inflation (D(INF)) at lags 0 and 2, (D(FDI)) at lags 1 and 2, energy consumption (D(LNEC)) at lags 1 and 2, and international trade (D(LNTRADE)) at lags 0, 1, and 2, indicating that these variables have a short-term influence on CO_2 emissions.

8. Long-Run ARDL Estimation

Table 1.11 Long-run ARDL results

Variable	Coefficient	Std. Error	t-Statistic	Prob.	Description
D(IR)	0.027061	0.007404	3.655061	0.0038	Significant
GDP	0.016947	0.003988	4.249492	0.0014	Significant

INF	0.001719	0.001328	1.294273	0.2221	Not significant
D(FDI)	-0.007631	0.014678	-0.519899	0.6134	Not significant
D(LNEC)	1.362123	0.412103	3.305298	0.0070	Signifikan
D(LNTO)	-0.442464	0.201842	-2.192132	0.0508	Signifikan
C	-0.038969	0.023514	-1.657311	0.1257	Not significant
EC = D(LNCO2(-1)) - (0.0271*D(IR) + 0.0169*GDP + 0.0017*INF - 0.0076 *D(FDI) + 1.3621*D(LNEC) - 0.4425*D(LNTO) - 0.0390)					

Source: Secondary data analysed using Eviews 12

The results of the long-run ARDL model estimates indicate that the benchmark interest rate (IR) has a positive and significant, with a coefficient of (3.655061, p = 0.0038 < 0.05). Economic growth (GDP) has a positive and significant effect, with a coefficient of (4.249492, p = 0.0014 < 0.05). Inflation (INF) has a positive effect however, it was not statistically significant, with a coefficient of (1.294273, p = 0.2221 > 0.05). Foreign direct investment (FDI) has a negative but insignificant effect, with a coefficient of (-0.519899, p = 0.6134 > 0.05). Energy consumption (EC) has a positive and significant effect with a coefficient of (3.305298, prob = 0.0070 < 0.05). Meanwhile, international trade openness (TO) has a negative but significant effect with a coefficient of (-2.192132, prob = 0.0508 < 0.05).

9. Hypothesis Testing

a. Coefficient of Determination (R^2)

Based on the results of the ARDL estimation, an R-squared value of 0.869878 and an adjusted R-squared value of 0.633294 were obtained. This R^2 value indicates that 86.99% of the variation in environmental pollution (CO_2 emissions) in Indonesia can be explained by the dependent variable. The remaining 13.01% is explained by other variables outside the research model.

b. F-Test (Simultaneous Test)

Based on the results of the ARDL estimation, the F-statistic value was 3.676815, with a critical F-value of 2.432 at $\alpha = 5\%$. Since the F-statistic value is greater than the F-table value, it can be concluded that the variables of interest rates, economic growth, inflation, foreign direct investment, energy consumption, and international trade openness collectively have a significant effect on environmental pollution in Indonesia.

c. t-statistic (Partial Test)

Based on the results of the long-run ARDL estimation, the following results were obtained:

1. The interest rate (IR)has a coefficient of 0.027061 with a probability of 0.0038 (< 0.05), indicating that it has a positive and significant effect on environmental pollution. This means that a 1% increase in the interest rate can increase CO_2 emissions by 0.027061 metric tonnes per capita in the long term.
2. Economic growth (GDP) has a coefficient of 0.016947 with a probability of 0.0014 (< 0.05), indicating that it has a positive and significant effect on environmental pollution. This means that a 1% increase in economic growth can lead to an increase in emissions of 0.016947 metric tonnes per capita in the long term.
3. Inflation (INF) has a coefficient of 0.001719 with a probability of 0.2221 (> 0.05), indicating a positive but insignificant effect on environmental pollution. This means that a

1% increase in inflation may, to a non-significant extent, increase CO_2 emissions by 0.001719 metric tonnes per capita in the long term.

4. Foreign Direct Investment (FDI) has a probability of 0.6134 (> 0.05), meaning it has a negative but insignificant effect on environmental pollution. This means that a 1% increase in foreign direct investment relative to GDP can reduce CO_2 emissions by -0.007631 metric tonnes per capita in the long term.
5. Energy Consumption (LNEC) has a coefficient of 1.362123 with a probability of 0.0070 (< 0.05), indicating a positive and significant effect on environmental pollution. This means that a 1% increase in energy consumption can increase CO_2 emissions by 1.362123 metric tonnes per capita in the long term.
6. International Trade Openness (LNTO) has a coefficient of -0.442464 with a probability of 0.0508 (= 0.05), indicating a negative and significant effect on environmental pollution. In other words, a 1% increase in international trade openness relative to GDP can reduce CO2emissions by -0.442464metric tonnes per capita significantly in the long term.

10. Stability Test

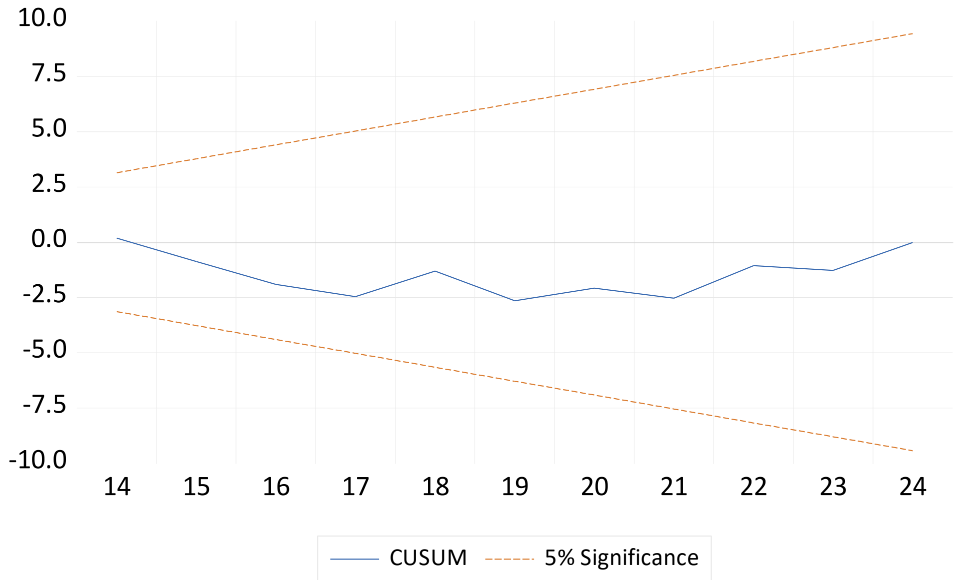


Figure 1. 3
Stability Test – Plots of Cumulatice Sum of Residual.
Source: Secondary data analysed using Eviews 12

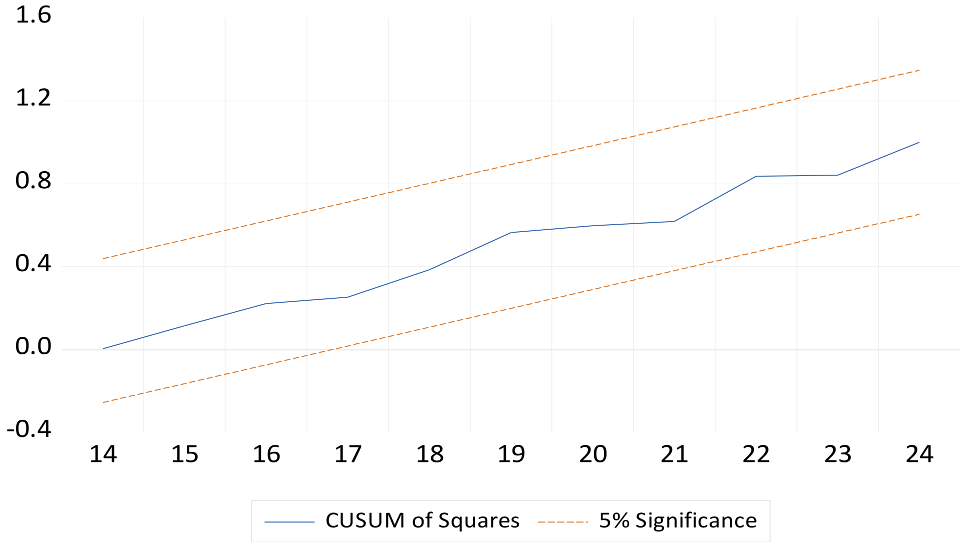


Figure 1. 16
Stability Test - Plots of Cumulatice Sum of Square Residual.
Source: Secondary data analysed using Eviews 12

Based on the results of the stability test using the CUSUM and CUSUM of Squares (CUSUMSQ) plots, it can be seen from the figure that all lines lie within the 5% confidence limit, meaning that the ARDL model is structurally stable. This indicates that there were no significant changes in the estimated parameters over the study period, either in terms of variance or the relationships between variables.

DISCUSSION

Based on the results of the ARDL estimation, interest rates have an impact on CO_2 emissions in the short term, whilst in the long term they have a significant impact on the increase in CO_2 emissions. Bank Indonesia's benchmark interest rate fluctuates in line with changes in national economic conditions, inflation, and monetary stability. In the early 1990s, interest rates were at high levels of around 18.90 per cent to 18.47 per cent, then rose sharply again to around 20.00 per cent during the 1997/1998 economic crisis as part of a tight monetary policy to curb inflation and maintain exchange rate stability. According to Annicchiarico and Di Dio (2017), an increase in interest rates leads to a rise in the discount rate, causing aggregate demand, industrial investment, consumption, and production activity to decline. This decline in economic activity leads to a reduction in fossil fuel consumption, thereby reducing carbon emissions and improving environmental quality. Conversely, when interest rates have fallen to the 3.50–6.00 per cent range in recent years, borrowing costs have become cheaper, driving increased investment, infrastructure development, industrialisation, and energy consumption, which ultimately increases carbon dioxide (CO_2) emissions. This situation is evident from the trend in Indonesia's carbon emissions, which have continued to rise from 0.73 tonnes per capita in 1989 to 2.87 tonnes per capita in 2024, indicating that increased economic activity and the use of fossil fuels remain the primary factors driving environmental pollution in Indonesia. These findings are consistent with research conducted by (Anastasiou et al., 2024) the study found that there is a positive and significant correlation between real interest rates and corporate carbon emissions, both total and direct. This means that when interest rates rise, companies tend to prioritise short-term financial stability and reduce investment in sustainable projects or environmentally friendly technologies. (Ullah et al., 2020) show that macroeconomic variables such as interest rates have a long-term relationship with carbon emissions in developing countries. Expansionary monetary policy can boost industrialisation and energy consumption, thereby increasing environmental pollution. (Wahyu et al., 2024) found that interest rate cuts boost economic growth whilst driving up per capita CO_2 emissions. Conversely, raising interest rates can slow economic growth and reduce per capita CO_2 emissions.

Meanwhile, based on the results of the ARDL estimation, economic growth (GDP) has an impact on the rise in CO_2 emissions in the long term. The rise in CO_2 emissions is attributed to Indonesia's economic structure, which is shifting from an agriculture-dominated economy towards industrialisation, the exploitation of natural resources, infrastructure development, and the expansion of the modern services sector. Based on Indonesia's economic growth data, the national economic growth rate has been relatively high, averaging 4.79 per cent per year, although it did contract by 13.13 per cent during the 1998 monetary crisis and by 2.07 per cent during the 2020 COVID-19 pandemic. According to BPS data, Indonesia's economic growth over the past few decades has tended to be driven by energy- and carbon-intensive sectors such as manufacturing, mining and quarrying, construction, transport and warehousing, as well as the expansion of natural resource-based industries such as coal and palm oil. The manufacturing sector has grown at a relatively stable rate of between 4 and 6 per cent per year and is one of the largest contributors to national GDP, driven primarily by the basic metals industry, which grew by 14.80 per cent in 2022 and 13.34 per cent in 2024, the chemical and pharmaceutical industry, which grew by 12.78 per cent in 2012, and the food and beverage industry, which grew by 10.98 per cent in 2011. Furthermore, the coal and lignite mining sector has shown very high growth, reaching 23.96 per cent in 2011, 15.73 per cent in 2012, and rising again to 10.02 per cent in 2023 in line with increasing domestic energy demand and commodity exports. National development activities are also reflected in the relatively stable growth of the construction sector, which remained above 5 per cent per year, even reaching 9.02 per cent in 2011, whilst the transport and warehousing sector grew by 19.87 per cent in 2022 and 13.96 per cent in 2023 following the post-COVID-19 recovery. On the other hand, the expansion of oil palm plantations as part of the plantation crops sub-sector also showed fairly high growth, such as 6.95 per cent in 2012 and 6.15 per cent in 2013, which contributed to land clearing and deforestation. This economic growth structure, dominated by sectors based on fossil fuels, the exploitation of natural resources, industrialisation, and transport, means that Indonesia's economic activities remain carbon-intensive and contribute to increased environmental pollution. This is reflected in the rise in Indonesia's per capita carbon dioxide (CO_2) emissions, which increased from 0.73 tonnes per capita in 1989 to 2.87 tonnes per capita in 2024—a rise of approximately 292.37 per cent over that period. These findings suggest that Indonesia is estimated to still be in the early phase of the Environmental Kuznets Curve (EKC), where economic growth is still accompanied by increased pressure on the environment, meaning that the scale effect remains more dominant than the technology effect. Consequently, the expansion of national economic activity has not yet been fully offset by environmentally friendly technological and production transformations; therefore, future development policies must be directed towards the transition to renewable energy, improving energy and industrial efficiency, and strengthening green economic policies so that economic growth can move towards decoupling economic expansion from environmental pollution. This finding is consistent with research conducted by (Maroufi & Hajilary, 2022), which shows that the impact of economic growth on CO2 emissions, in the long term, follows a

U-shaped curve in Iran. Research by (Nikensari et al., 2019) also found that the inverted U-shaped EKC hypothesis has not yet materialised in the high-income countries studied, but will occur once GDP per capita reaches USD 51,440. Meanwhile, in lower-middle-income countries, the relationship between GDP per capita and CO2 emissions still follows a U-shaped curve; in other words, the EKC hypothesis has not yet materialised in these countries, as some of them are still in the early stages of development.

Based on the results of the short-run ARDL estimation, it was found that inflation (INF) affects CO_2 emissions, whereas in the long run, inflation (INF) has a positive but insignificant effect on CO_2 emissions. These findings can be explained by the theory of demand-pull inflation proposed by John Maynard Keynes, which states that excessively high inflation can hinder economic growth by reducing the public's purchasing power. The situation in Indonesia, where inflation is largely driven by electricity and household fuel tariffs (BPS, 2025), reflects that the reduction in emissions due to inflation is temporary, as the energy structure remains reliant on fossil fuels and technological transformation has not yet progressed rapidly. These findings are consistent with research (Grolleau & Weber, 2023) that found a slight negative correlation between inflation and carbon emissions across 189 countries, suggesting that moderate inflation can curb energy consumption. Meanwhile, (AlShafeey & Saleh Saleh, 2024) show a non-linear response of GHG emissions to inflation rates. In the US, GHG emissions began to decline when the inflation rate exceeded 4.7%. Similarly, in the EU, a sharp decline in emissions was observed when inflation exceeded 7.5%. China exhibits a more complex pattern, with two critical turning points: the first at an inflation rate of 4.5%, at which point GHG emissions began to decline sharply, and the second at an inflation rate of 7%, at which further increases in inflation did not significantly reduce emissions.

Based on the results of the short-run ARDL estimation, it was found that foreign direct investment (FDI) does not have a significant effect in the short run, whereas in the long run, FDI has a negative but insignificant effect on CO2 emissions. This phenomenon supports the Pollution Haven Hypothesis proposed by Copeland & Taylor (1994), which states that such impacts can drive economic growth and the transfer of clean technology (the pollution halo effect). With economic growth driven by investment, Indonesia needs to strengthen incentives for green investment, energy efficiency regulations, and industrial carbon standards to ensure that FDI's contribution aligns with national emission reduction targets. In line with the findings (Apergis et al., 2023), a study examining the relationship between bilateral FDI and emissions in BRICS countries using an ARDL panel approach found that FDI from developed countries tends to reduce emissions through the adoption of environmentally friendly technologies. (Demena & Afesorgbor, 2020). A meta-analysis of 65 studies found that the average effect of FDI on global emissions is close to zero, but the direction of this effect depends heavily on the investment sector and the environmental regulations of the host country.

Based on the results of the short-run ARDL estimation, it was found that Energy Consumption (EC) has an impact on CO_2 emissions. In the long run, however, Energy Consumption (EC) has a positive and significant impact on CO_2 emissions. This finding indicates that in Indonesia, energy consumption is a dominant factor in the increase in CO2 emissions through the scale effect of economic expansion, and that energy consumption remains more dominant than the technique effect due to the dominance of coal in the national energy mix; high energy consumption in the manufacturing and transport sectors, as well as large-scale infrastructure projects, means that any increase in energy consumption leads to a rise in CO2 emissions. This situation is consistent with research conducted by Jian et al. (2019) which shows that energy consumption and financial development have a significant positive impact on CO_2 emissions in the long term, whilst economic growth can only reduce emissions when supported by financial innovation and structural transformation. Meanwhile, Hwang & Yoo (2015) indicate a two-way causal relationship between energy consumption and CO_2 emissions in Indonesia, such that increased energy consumption not only drives emissions but also creates a feedback loop in the form of increased energy demand resulting from the expansion of carbon-based economic activities. With fossil fuels still accounting for 86.92% of the energy mix in 2024 (ESDM, 2024), these findings underscore the urgency of accelerating the energy transition, increasing investment in clean energy, and implementing carbon taxes and emissions trading mechanisms to reduce emissions sustainably.

International trade (TO) has a significant negative impact on CO2 emissions in the long term. These results suggest that trade acts as a channel for environmental improvement through technological and composition effects, whereby the introduction of efficient production technologies, global production standards, and the diversification of exports in value-added sectors reduces carbon intensity. These findings are consistent with research (Ma & Ogata, 2024) which confirms that economic complexity and the diversification of export products influence energy efficiency and emission levels, with countries with a high-tech production base tending to generate lower emissions. Similar findings were also reported in the study (Romero & Gramkow, 2021) indicates that countries with a high-tech production base and high trade openness tend to generate lower emissions. According to the Indonesian Sustainable Trade and Investment Report 2024, Indonesia's exports and imports of environmental goods remain relatively low but are growing, underscoring the potential for increased green trade to support national decarbonisation and the energy transition. Therefore, trade policy should be directed towards strengthening exports of environmentally friendly products, applying carbon standards to industrial imports, and monitoring international supply chains based on sustainability. (ISTIR, 2024).

CONCLUSION

Economic growth has been shown to increase carbon emissions, indicating that Indonesia remains in the early stages of the Environmental Kuznets Curve (EKC), where the scale effect of economic growth is more dominant than the technology effect. Energy consumption is the strongest determinant of rising emissions, reflecting Indonesia's high dependence on fossil fuels. Foreign direct investment (FDI) shows an insignificant impact in the long term, although in the short term it has a delayed positive effect on emissions, indicating that the impact of FDI is highly dependent on the target sector and the quality of environmental regulations. The benchmark interest rate has a positive and significant effect; in the long term, an increase in interest rates is actually correlated with a rise in emissions due to the hindrance of green investment, in line with John Maynard Keynes's view on long-term investment. Inflation does not show a significant impact on the reduction of CO2 emissions in Indonesia. Meanwhile, international trade openness plays a significant role in reducing carbon emissions, indicating the presence of a 'technique effect' and a 'composition effect' through the adoption of more efficient technologies and global environmental standards. Overall, these results illustrate that the complexity of Indonesia's macroeconomy makes a tangible contribution to changes in environmental pollution levels. Indonesia's macroeconomic dynamics, characterised by stable GDP growth of 5% and projected to rise to 8% by 2029 industrial expansion, reliance on fossil fuels, and global pressures to enhance competitiveness have created significant strain on environmental quality, as evidenced by widespread environmental damage across various regions in Indonesia, such as hydrometeorological disasters (floods and landslides), deforestation, plastic pollution, air pollution, and damage caused by mining activities. Although the government has implemented various regulations such as the Law on Environmental Protection and Management (Law No. 32/2009), Environmental Impact Assessments (EIA), green industry certification, and carbon tax policies, in practice, challenges remain in the form of weak law enforcement, high levels of non-compliance within industry, and trade-offs between economic and ecological interests. Therefore, strengthening environmental regulation enforcement policies, green monetary policies, and inflation control that does not sacrifice environmentally friendly investment; promoting industrial transition towards low-carbon energy sources; accelerating the energy transition; implementing the circular economy and Industry 4.0 technologies; and the development of green economy-based trade are crucial strategies to ensure that Indonesia's economic growth can proceed in tandem with the commitment to reduce emissions by 31.89% by 2030, in line with the Enhanced Nationally Determined Contribution (NDC).

The government needs to strengthen the synergy between macroeconomic and environmental policies to ensure that economic growth does not have a negative impact on environmental quality. This can be achieved through improved energy efficiency, the adoption of environmentally friendly technologies, and the strengthening of environmental regulations in production and industrial activities. Furthermore, policies on foreign direct investment and international trade need to be directed more selectively so that they are not dominated by energy-intensive and high-emission sectors, but rather encourage green investment and the development of low-carbon, value-added industries. Accelerating the transition to renewable energy and improving energy consumption efficiency across various sectors must also be continuously optimised to reduce dependence on fossil fuels. Thus, the integration of economic, energy, and environmental policies is expected to support the achievement of national emission reduction targets by 2030 and realise the Net Zero Emission 2060 commitment sustainably.

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